Multisite Analyses of Spectral–Biophysical Data for Sorghum

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*Spectral–biophysical functional relations that hold across experiments and environments are needed for economically important crops. Thus, reflectance factors and leaf area index (LAI) measurements for sorghum [*Sorghum bicolor *(L.) Moench] experiments conducted at Bushland, Texas (102.2°W, 35.2°N), Lubbock, Texas (101.8°W, 33.7°N), and Weslaco, Texas (98.0°W, 26.2°N) over a 7-year period were related using two-parameter power and exponential equations for four common vegetation indices (VI): normalized difference (NDVI), perpendicular (PVI), near-infrared to red ratio (RVI), and transformed soil-adjusted (TSAVI). The objective was to produce recommendable empirical equations for estimating LAI of sorghum from spectral vegetation indices using observations pooled across locations. During both the pre- and post-maximum leaf area index portions of the growing season, power and exponential forms were equally good for estimating LAI from TSAVI and NDVI and gave coefficients of determination, R^2, that ranged from 0.76 to 0.83. However, for PVI and RVI the relations were not as nonlinear and the power form accounted for more of the variation ($R^2 = 0.74$–0.82) than the exponential form ($R^2 = 0.69$–0.78). Infinite reflectance for sorghum was estimated from the pooled data to be 4.0% in the RED band and 49.7% in the NIR band. Coefficients of exponential relations for sorghum were similar to those for corn reported earlier. Although soils, agronomic treatments, sun angles, and instruments differed among locations, it was possible to develop general relations for estimating leaf area of sorghum from four of the most commonly used spectral vegetation indices.*

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INTRODUCTION

Current and prospective users of remote observations of economically important crops and other ecosystems need spectral–biophysical functional relations that are valid across locations and environments. However, most literature reports de-

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scribe experiments in which one or more cultivars of one crop species were studied at one location for one or more crop seasons. In a few instances, comparisons have been made for three or more species at one location (Dusek and Musick, 1986; Redelfs et al., 1987; Wiegand and Richardson, 1987; Wanjura and Hatfield, 1988), but results are not readily comparable because the same plant and spectral parameters were not measured and equation forms employed were nonuniform. Among-site comparisons are even more difficult because of variation in sun zenith angle (latitude, planting date, and time of day of observations), soil and surface conditions, instrument and measurement techniques, canopy architecture (leaf angle, canopy openness, height), and cultural practices (row spacing, plant population, fertilization).

To help provide the needed relationships, the Spectral–Agronomic Multisite–Multicrop Analyses (SAMMA) Project (Wiegand and Hatfield, 1988) was initiated. Under SAMMA, reflectance data from handheld and boom-mounted spectroradiometers and agronomic or biophysical plant measurements have been pooled across locations for uniform analysis for the crops wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], soybean (*Glycine max* Merr.), cotton (*Gossypium hirsutum* L.), and alfalfa (*Medicago sativa* L.). Wiegand et al. (1990; 1992) have analyzed multisite data for corn and wheat. In this companion paper, data from sorghum experiments conducted at Bushland, Texas, Lubbock, Texas, and Weslaco, Texas (Table 1) are analyzed within and among locations. The objective was to develop empirical relations between several vegetation indices and leaf area index that could be recommended for general use.

METHODS AND MATERIALS

Data were pooled from eight sorghum experiments (Table 1) conducted at three locations over a period of 7 years (Dusek and Musick, 1986; Steiner, 1986; Wanjura and Hatfield, 1986; 1988; Richardson et al., 1990). Co-authors provided re-

Table 1. Treatments, Cultivars, and Growth Characteristics of Grain Sorghum [*Sorghum bicolor* (L.) Moench] in the Experiments of This Study

Location; Latitude; Longitude; (degree)	*Year*	*Treatments Used*	*Cultivars*	*Grain Yield (kg/ha)*	*Plant Population (no./m²)*	*Phenology*		
						Emergence	*Heading (DOY)*	*Black Layer*
Bushland, TX; 102.2°W 35.2°N	1982	Irrigation (eight treatments)	Pion. 8333			165	210	279
						165	210	279
						165	210	279
						165	210	279
							210	279
	1983	Irrigation (eight treatments)	Pion. 8333			175	230	279
						175	230	279
						175	230	279
						175	230	279
	1984	Population row spac. and direc.	Hybrid DK46	3340	5.4	165	235	272
				3200	7.8	165	235	272
				3390	11.5	165	235	272
Lubbock, TX; 101.8°W 33.6°N	1984	Irrigation study L, H	Funks G522DR	7710	40.2	148	208	249
				4730	40.2	148	208	249
	1985	Irrigation study L, H	Funks G522DR	5950	19.2	154	204	249
				2870	20.4	154	204	249
Weslaco, TX; 98.0°W 26.2°N	1987	Tillage & nitrogen study	Oro G-XTRA	8030	11.8	85	146	180
	1988	Tillage & nitrogen study	Oro G-XTRA	2720	9.0	89	146	182
	1989	Commercial field study	Funks 522VR	6950	28.2	71	132	170

Table 2. Instruments, Wavelengths, and Their Use by Experimental Sites

MMR 12-1000		Mark-II	
Band	*μm*	*Band*	*μm*
1	0.45–0.52		
2	0.52–0.60		
3[a]	0.63–0.69	1[b]	0.63–0.69
4[a]	0.76–0.90	2[b]	0.76–0.90
5	1.15–1.30		
6	1.55–1.75		
7	2.08–2.35		

[a] MMR3 and MMR4 correspond to the RED and NIR bands, respectively, for Bushland and Lubbock in this study.
[b] Similarly, the Mark-II Bands 1 and 2 correspond to the RED and NIR bands, respectively, for Weslaco.

flectance factors for each band of each instrument used (Table 2), plant leaf area index (m^2/m^2), and above ground phytomass (g/m^2) by treatment.

Field experiments and biophysical measurements. Plant populations, dates of cardinal phenological events, cultivars used, grain yields, and treatments imposed are summarized in Table 1. At Bushland and Weslaco, row spacing was 0.76 m and at Lubbock row spacing was 1 m. Row direction was both N–S and E–W in 1984 and N–S in 1982 and 1983 at Bushland, and E–W at Lubbock and Weslaco all years. Green leaf area index (L) and above-ground dry phytomass (DM, g/m^2) were measured at sampling intervals that varied from weekly to biweekly between emergence and harvest.

Reflectance factors and vegetation indices. Reflectance factor measurements (percent) were acquired with Barnes Modular Multiband 12-1000 Radiometers (MMR) (Robinson et al., 1979) at Bushland and Lubbock, and a Mark II radiometer (Tucker et al., 1981) at Weslaco (Table 2). All measurements were obtained within 2 h of solar noon. The Bushland and Lubbock MMR instruments had fields of view of 15°, were boom-mounted, and measurements were made looking vertically downward from 5 to 8.5 m above the ground. At Bushland and Lubbock, reflectance factors are relative to $BaSO_4$ reflectance standards. The Weslaco Mark II instrument was hand-held, and measurements were made from 1 to 1.5 m above the canopy and averaged over the plant furrow and plant row. The Mark II field of view was 24° in 1987 and 15° in 1988 and 1989. At Weslaco reflectance factors are relative to a Halon reflectance standard. For this study MMR spectral Bands 3 and 4 and Mark-II spectral Bands 1 and 2 were used for RED and NIR reflectance factor measurements (Table 2) at sampling intervals that varied from weekly to biweekly from emergence to harvest.

Four commonly used vegetation indices (VI), perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977), normalized difference (NDVI), NIR/RED ratio (RVI) (Tucker, 1979), and the transformed soil adjusted vegetation index (TSAVI) (Baret et al., 1989) were calculated as follows:

$$\mathrm{PVI} = [\mathrm{NIR} - a(\mathrm{RED}) - b]/(1 + a^2)^{1/2}, \quad (1)$$

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}), \quad (2)$$

$$\mathrm{RVI} = \mathrm{NIR}/\mathrm{RED}, \quad (3)$$

and

$$\mathrm{TSAVI} = \frac{a[\mathrm{NIR} - a(\mathrm{RED}) - b]}{[\mathrm{RED} + a(\mathrm{NIR}) - ab]}. \quad (4)$$

a and b of Eqs. (1) and (4) are the slope and intecept, respectively, of the soil line,

$$\mathrm{NIR} = a(\mathrm{RED}) + b \quad (5)$$

Table 3. Soil Line and Vegetation Index Equations by Year, Location, and Radiometer

Location	*Year*	*Radiometer*	*Soil Line and Vegetation Index Equations*
Weslaco	1987	Mark-II	NIR = 2.0 + 1.16 RED
Weslaco	1989	Mark-II	PVI = 1.31 − 0.76 RED + 0.65 NIR
Bushland	1982	MMR	TSAVI = 1.16 (NIR − 1.16 RED
Bushland	1983	MMR	− 2.0) / (RED + 1.16 NIR − 2.32)
Lubbock	1984	MMR	NIR = 4.0 + 1.24 RED
Lubbock	1985	MMR	PVI = 2.51 − 0.78 RED + 0.63 NIR
Bushland	1984	MMR	TSAVI = 1.24 (NIR − 1.24 RED
Weslaco	1988	Mark-II	− 4.0) / (RED + 1.24 NIR − 4.95)

for each experimental site as estimated from NIR versus RED scatter diagrams. The soil line coefficients and the PVI and TSAVI vegetation index equations are given by location and instrument in Table 3. The VI were divided into pre-L_{max} and post-L_{max} intervals and paired with L estimated from linear interpolation based on the time of actual VI measurements.

Equation forms and analysis procedures. Several equation forms have appeared in the literature for estimating L from VI (Maas et al., 1985; Maas, 1988a,b; Wiegand and Richardson, 1987). These models involved two- and three-parameter exponential equations that related L to VI for wheat, cotton, and corn. Two-parameter power equations significantly related all two band VI to L for corn (Wiegand et al., 1990). For multisite wheat data, linear equations produced significant relations of RVI to L, but two-parameter exponential equations best related NDVI and TSAVI to L (Wiegand et al., 1992).

In this study we used the two-parameter exponential and power regression models for all four of the VI used in this study,

$$L = A[\exp(B*\mathrm{VI})], \tag{6}$$

and

$$L = A(\mathrm{VI}**B), \tag{7}$$

where

L = green leaf area index,
VI = any of the four vegetation indices TSAVI, PVI, NDVI, or RVI,

and A and B are coefficients.

For treatment within location analyses the 95% confidence bands about the coefficients A and B were computed for each vegetation index and examined to determine whether the functional relations by vegetation index overlapped. Confidence bands were also used to compare pre- and post-L_{max} relations among locations. Analysis utilized nonlinear Plot IT™ (Eisensmith, 1987) and SAS (SAS Institute, 1988) statistical procedures.

RESULTS

Sorghum data used for this study were obtained under very diverse planting dates, length of season, ambient temperature, and moisture conditions that created large variations in canopy L and DM development (Fig. 1). The crop season for Bushland and Lubbock occurs during long midsummer days whereas it ends at Weslaco before July. Poor seedbed and weed problems resulted in lower L and DM canopy development at Weslaco in 1988. Cool, dry weather in 1984 produced unusually slow L and DM canopy development at Bushland while unusually warm weather in 1982 resulted in rapid canopy development. Canopy development at Lubbock was faster in 1984 than in 1985 due to a more favorable growing season (Wanjura and Hatfield, 1988). Reflectance factors in the RED were more uniform at all locations than in the NIR.

Figure 2 is similar to Figure 1 for L except that DOY has been normalized [$T = (\mathrm{DOY} - \mathrm{EM}) / (\mathrm{PM} - \mathrm{EM})$] so that $T = 0$ corresponds to emergence (EM) and $T = 1$ corresponds to physiological maturity (PM). The curves match better among locations, except the unusually rapid canopy development at Bushland in 1982 is apparent. From these curves we visually divided the growing season for all locations and years into pre-L_{max} and post-L_{max} portions at $T = 0.72$ for all analyses of L versus the four VIs. The $TR = 0.72$ time was the best visual estimate for dividing the end of peak plant development and the beginning of senescence.

The PVI versus T curves of Figure 2 corresponds well in position and shape to the L versus T curves. The faster plant development and senescence under the very warm temperatures at Weslaco result in more of a peak than a plateau in L and PVI during grain filling.

Within-location analyses. Within-location results were examined to learn whether agronomic treatments affected the L versus VI relations. However, since there was disparity in experimental designs among years within locations (Table 1), we examined the agronomic treatment effects indirectly by comparing the confidence bands around the mean values of the coefficients A and B for the Eq. (7) functional relation between L and VI for each location and year and then for the pooled location data summed over years.

We found that for Bushland and Weslaco the A's and B's differed significantly when vegetation growth was poor. For example, at Bushland the vegetation indices TSAVI, NDVI, and RVI the A's

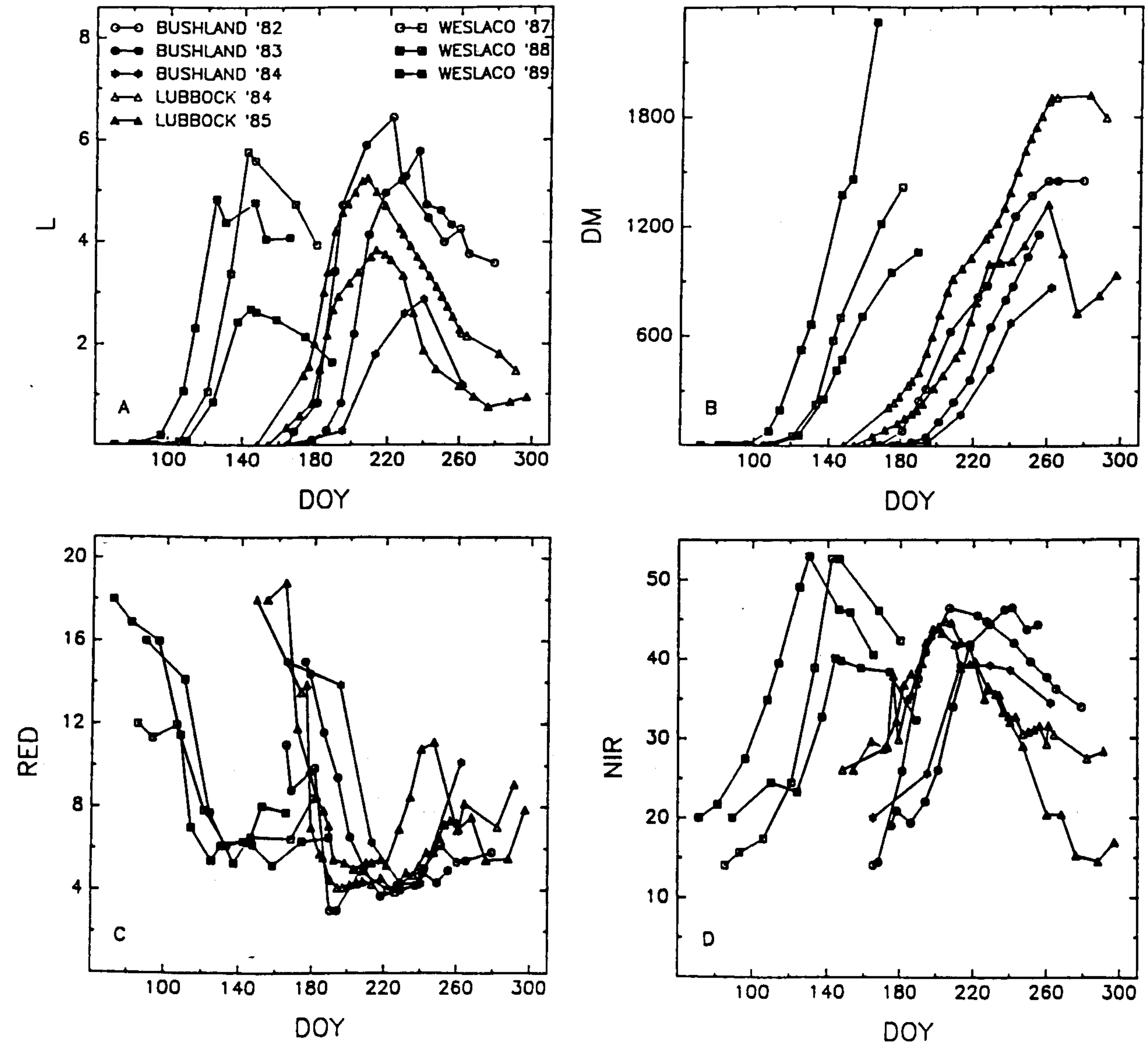


Figure 1. Seasonal leaf area index (L), above-ground dry phytomass (DM), near-infrared (NIR), and visible red (RED) reflectance factors (in percent) for each location and year of this study.

for the 1984 data, when growth was slowed by cool weather, differed from those for the 1982 and 1983 data and from those for all the years pooled, whereas the B's did not differ among years or for the data pooled across years. For Weslaco, the confidence bands around A and B for 1988, when growth was slowed by poor seedbed and weed problems, differed from those in 1987 and 1989 and from those for the 3 years pooled for all VI. In contrast, at Lubbock, the experimental design was the same for both 1984 and 1985 and for all VI the A and B confidence bands overlapped over the complete L versus VI range. Thus complications from incomplete cover due to interseasonal growth differences were evidently more important than agronomic treatments.

The within-location power equation (7) relations between L and the four VIs (Fig. 3) for the pre-L_{max} portion of the growing season show that TSAVI and NDVI are more curvilinearly related to L than are PVI and RVI. The curves for NDVI and TSAVI are very similar in shape because NDVI is the special case of TSAVI in which the slope of the soil line is 1 and the line goes through the origin. TSAVI begins closer to the origin than NDVI because TSAVI = 0 for $L = 0$ whereas NDVI

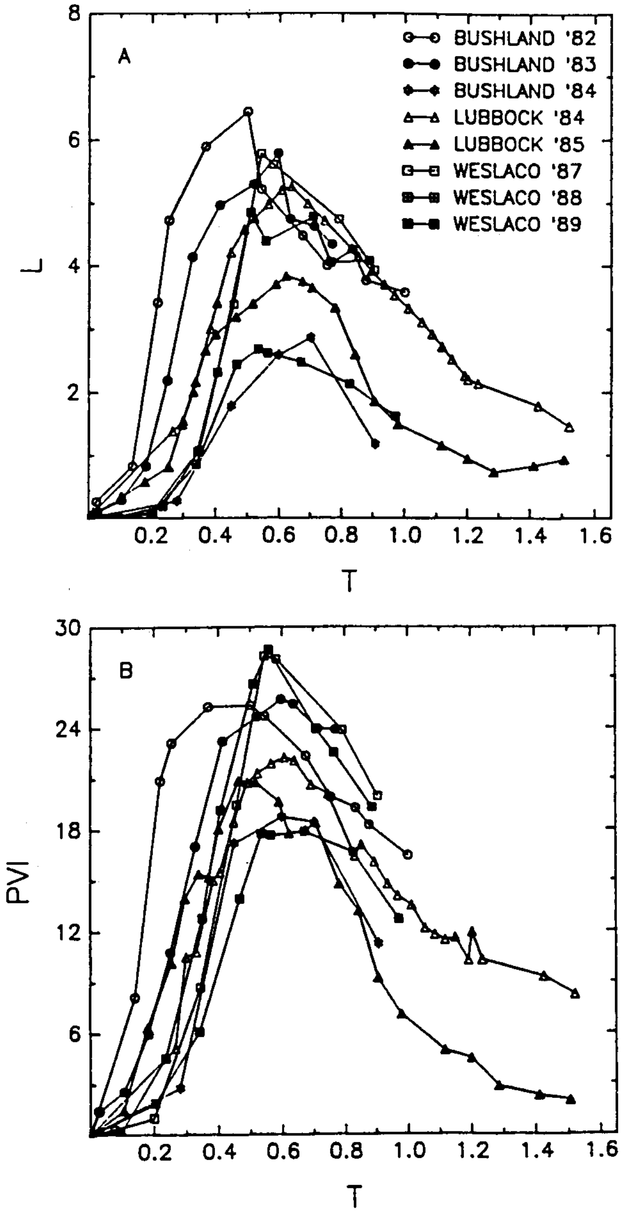


Figure 2. Similar to Figure 1 except that day of year (DOY) has been normalized between emergence (EM) and physiological maturity (PM) so that $T = (DOY - EM)/(PM - EM)$ and the vegetation index PVI is displayed.

of the soil is usually about 0.2 as in these experimental observations.

In Figure 3 the equations for Weslaco closely resemble those for Bushland and Lubbock only for PVI. The effects of instrumental, measurement, and/or calibration technique differences, which made the Weslaco reflectance factors higher than at Bushland and Lubbock (Figure 1), cause TSAVI, NDVI and RVI to be more curvilinear for Weslaco than for Bushland and Lubbock data.

Within location coefficients for Eqs. (6) and (7), coefficients of determination (R^2), and root mean square errors (RMSE) in estimating L (Table 4) for both pre- and post-L_{max} portions of the season show that the soil adjusted vegetation indices have less overall scatter than the vegetation indices that are not adjusted for soil reflectance. In most instances, the TSAVI and PVI have higher coefficients of determination (R^2) and lower RMSE than either the NDVI or RVI. An exception was found for the pre-L_{max} part of the season at Lubbock where the NDVI gave the best fit. Overall, the RMSE for the Bushland data were much higher than for the Lubbock and Weslaco data. This may have resulted from many observations at Bushland of high L where the vegetation indices are insensitive. The R^2 for Bushland were also lower in the post-L_{max} part of the season than those for Lubbock and Weslaco.

In Table 4 the power and exponential forms give essentially the same R^2 and RMSE values for TSAVI and NDVI, but the power equations give higher R^2 and lower RMSE for PVI and RVI. Examination of the residuals for data collected during the pre-L_{max} part of the season (not shown) revealed that application of the exponential equation to RVI and PVI seriously overestimated L values below 2. The exponential equations did follow the observed values of TSAVI and NDVI over their whole range. For this reason, both the power and exponential equations are endorsed for estimating TSAVI and NDVI, but only the power form can be recommended for estimating PVI and RVI. In the data sets of this study, L observations greater than 2 were most numerous (Fig. 3) and dominated the statistical fits, making it advisable to examine estimation equation fits to low L values for all vegetation indices.

For both corn (Wiegand et al., 1990), which included data from Bushland but not Lubbock, and wheat (Wiegand et al., 1992), which included data from Lubbock but not Bushland, the relations for ratio vegetation indices were also more curvilinear for Weslaco than the other locations. For both those data sets and the one for sorghum herein, reflectance factors for Weslaco were high in both the RED and NIR for midrange values of L. The ratio vegetation indices RVI, NDVI, and TSAVI are more sensitive to such inconsistencies among locations than are orthogonal indices such as PVI.

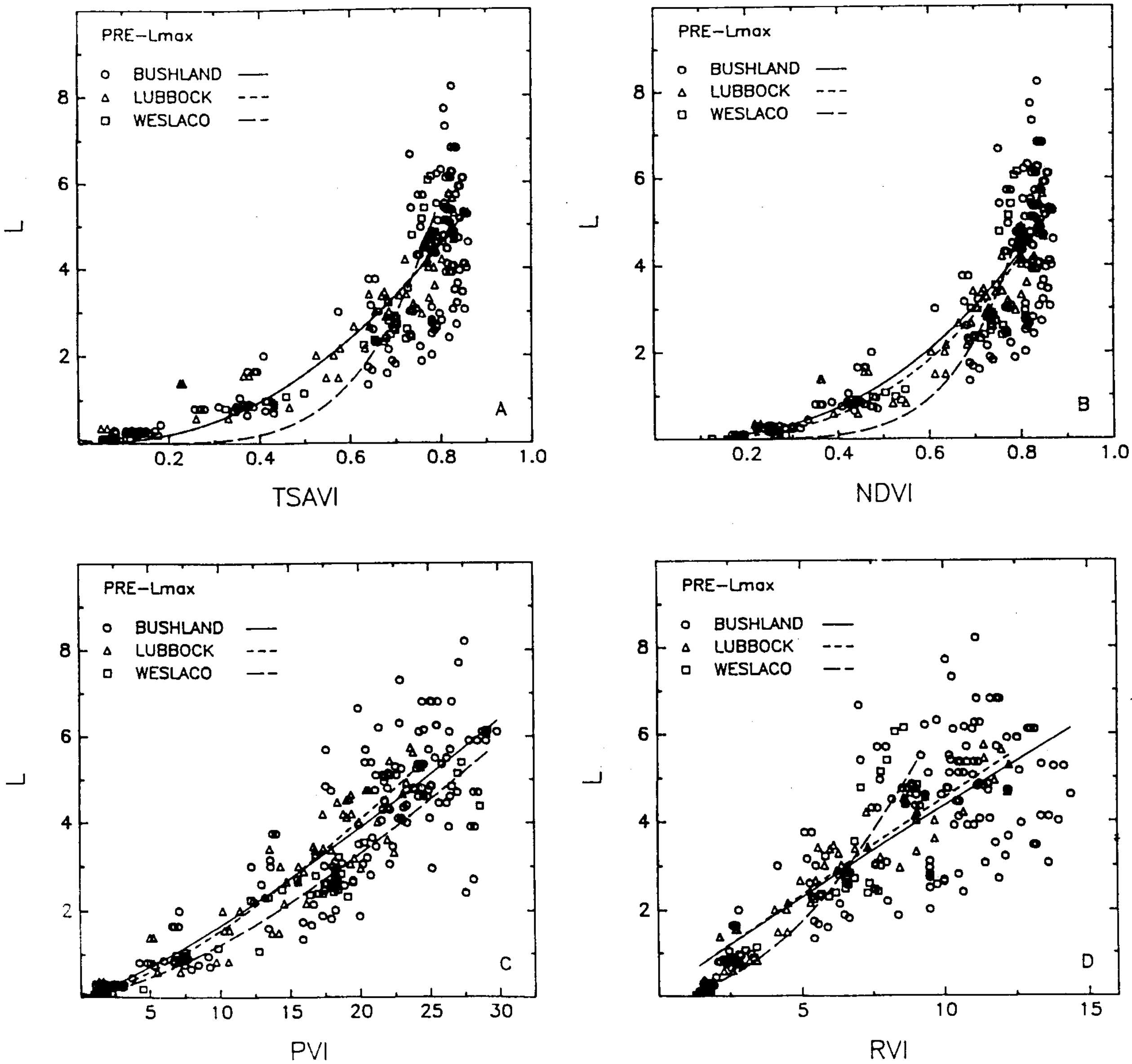


Figure 3. Relation between L and the vegetation indices TSAVI, NDVI, PVI, and RVI for by location the pre-L_{max} portion of the growing season as fit by the two parameter power equation, $L = A(\mathrm{VI}{*}{*}B)$.

Among-location analyses. Analyses of the data pooled among locations (Fig. 4) show that both the exponential and power equations (Table 5) adequately described the relation between L pooled across locations for TSAVI and NDVI as had been the case (Table 4) for within location results. However, the power equation remained a better form for PVI and RVI. The power equations follow the observed data well over the whole range. For PVI and RVI the exponential equations (not shown) overestimated L at values below 2 as they did for the within location data discussed earlier. Thus, the power and exponential equation forms are equally desirable for estimating TSAVI and NDVI but only the power equation is recommended for estimating L from PVI and RVI.

For Eq. (6), plots of $\ln(L)$ versus VI are linear with slopes equal to B, so that it is evident that incorporation of the slope and intercept of the soil line into NDVI to produce TSAVI [Eq. (4) vs. Eq. (2)] reduces B in TSAVI versus ln(L) relations compared with those for NDVI. Thus TSAVI reaches an asymptotically limiting value at a slower rate than NDVI does with increasing L, which

Table 4. Within Location Two-Parameter Power and Exponential Equation Coefficients, Coefficients of Determination (R^2), and Root Mean Square Error (RMSE) by Vegetation Index for the Pre-L_{max} and Post-L_{max} Portions of the Growing Season

Location (No. Obs.)	Vegetation Index	Power Eq. Form $L=A(VI**B)$ A	B	R^{2a}	RMSE (m^2/m^2)	Exponential Eq. Form $L=A(exp(B*VI))$ A	B	R^{2a}	RMSE (m^2/m^2)
A. Pre-L_{max}									
Bushland	TSAVI	7.507	2.246	0.75	1.12	0.256	3.580	0.75	1.12
(172)	NDVI	7.661	2.581	0.73	1.15	0.171	4.005	0.73	1.16
	PVI	0.097	1.230	0.80	1.00	0.819	0.073	0.76	1.09
	RVI	0.509	0.932	0.70	1.21	1.157	0.124	0.61	1.40
Lubbock	TSAVI	7.592	2.261	0.88	0.53	0.297	3.436	0.90	0.49
(50)	NDVI	8.104	2.932	0.88	0.51	0.079	3.571	0.90	0.48
	PVI	0.061	1.399	0.83	0.62	0.730	0.085	0.82	0.65
	RVI	0.504	0.954	0.89	0.50	1.191	0.131	0.82	0.65
Weslaco	TSAVI	16.953	4.894	0.88	0.62	−0.0015	5.284	0.90	0.58
(43)	NDVI	18.026	5.808	0.84	0.72	−0.0065	5.644	0.85	0.70
	PVI	0.045	1.432	0.96	0.36	0.595	0.080	0.93	0.49
	RVI	0.081	1.905	0.86	0.67	0.326	0.321	0.85	0.70
B. Post-L_{max}									
Bushland	TSAVI	8.394	2.398	0.86	0.49	0.277	3.621	0.85	0.51
(41)	NDVI	9.354	3.033	0.85	0.51	0.155	4.290	0.83	0.54
	PVI	0.089	1.262	0.68	0.75	1.011	0.066	0.61	0.82
	RVI	0.561	0.976	0.78	0.62	1.403	0.135	0.67	0.76
Lubbock	TSAVI	6.912	1.760	0.92	0.35	0.445	2.999	0.94	0.32
(47)	NDVI	7.667	2.495	0.92	0.36	0.215	3.792	0.92	0.36
	PVI	0.152	1.160	0.93	0.33	0.870	0.090	0.89	0.42
	RVI	0.555	0.954	0.90	0.41	1.167	0.147	0.79	0.58
Weslaco	TSAVI	15.719	4.106	0.47	0.99	0.049	6.142	0.47	0.98
(14)	NDVI	11.552	3.874	0.21	1.20	0.058	5.584	0.22	1.20
	PVI	0.013	1.867	0.90	0.42	0.471	0.099	0.90	0.44
	RVI	0.231	1.448	0.23	1.19	0.671	0.252	0.24	1.18

[a] (Total corrected sum of squares − residual sum of squares)/total corrected sum of squares. Applies, also, to Tables 5 and 6.

also improves the fit of TSAVI data to Eq. (6) (Table 5).

In Eq. (6) the closer B approaches 0, the more linear the relation, and for Eq. (7) the closer B approaches 1, the more linear it becomes. For RVI, B in Eq. (7) during the pre-L_{max} part of the season was 0.96 and during the post-L_{max} part it was 0.99. As can be seen in Figure 4d, L(RVI) was nearly linear. For RVI the linear equations were

$$L(\text{pre-}L_{max}) = -0.171 + 0.459(\text{RVI}),\quad r^2 = 0.74, \tag{8}$$

$$L(\text{post-}L_{max}) = -0.135 + 0.543(\text{RVI}),\quad r^2 = 0.77, \tag{9}$$

For PVI, B in Eq. (7) was 1.27 for the pre-L_{max} and 1.03 for the post-L_{max} part of the season (Table 5). For comparison, the linear equations were

Table 5. Combined Location Two-Parameter Exponential and Power Equation Relations By Pre-L_{max} and Post-L_{max} Portions of the Growing Season

Equations	Part of Season	R^2	RMSE
A. Exponential			
1. $L=0.241$ exp[3.667(TSAVI)]	Pre-L_{max}	0.78	0.97
$=0.139$ exp[4.26(NDVI)]		0.76	1.00
$=0.812$ exp[0.0729(PVI)]		0.78	0.98
$=1.142$ exp[0.127(RVI)]		0.64	1.25
2. $L=0.345$ exp[3.331(TSAVI)]	Post-L_{max}	0.83	0.55
$=0.171$ exp[4.130(NDVI)]		0.80	0.60
$=1.073$ exp[0.065(PVI)]		0.70	0.74
$=1.243$ exp[0.146(RVI)]		0.69	0.75
B. Power			
1. $L=7.812$(TSAVI**2.422)	Pre-L_{max}	0.78	0.98
$=8.151$(NDVI**2922)		0.76	1.01
$=0.084$(PVI**1.273)		0.82	0.88
$=0.479$(RVI**0.963)		0.74	1.06
2. $L=7.671$(TSAVI**2.103)	Post-L_{max}	0.82	0.56
$=8.626$(NDVI**2.830)		0.80	0.60
$=0.183$(PVI**1.033)		0.74	0.68
$=0.531$(RVI**0.991)		0.77	0.65

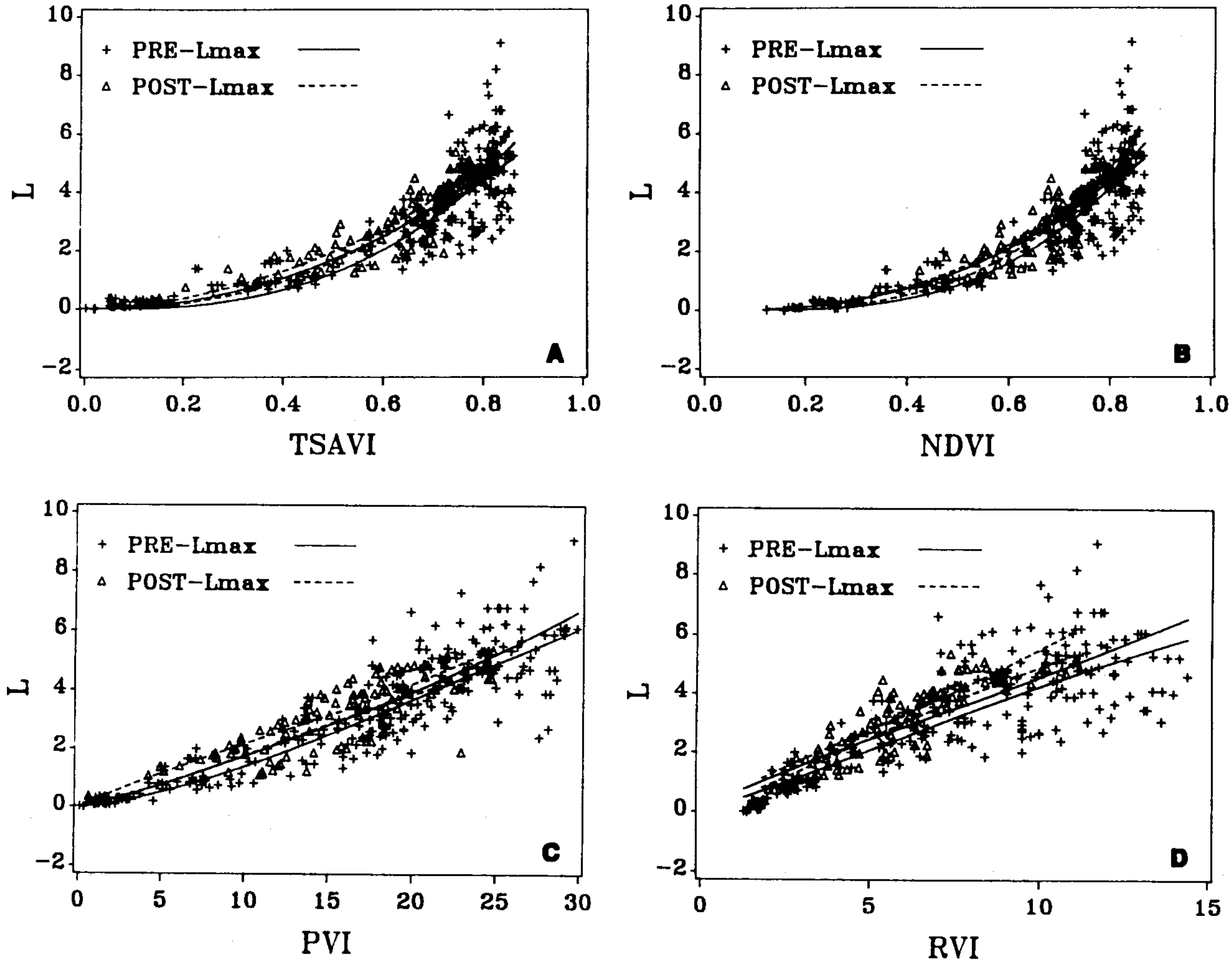


Figure 4. Data for all locations pooled and 95% confidence intervals for power equations of Table 5 that describe the data by pre-L_{max} (pluses) and post-L_{max} (triangles) portions of the season.

$$L(\text{pre-}L_{max}) = -0.389 + 0.214(\text{PVI}),\quad r^2 = 0.81, \tag{10}$$

and

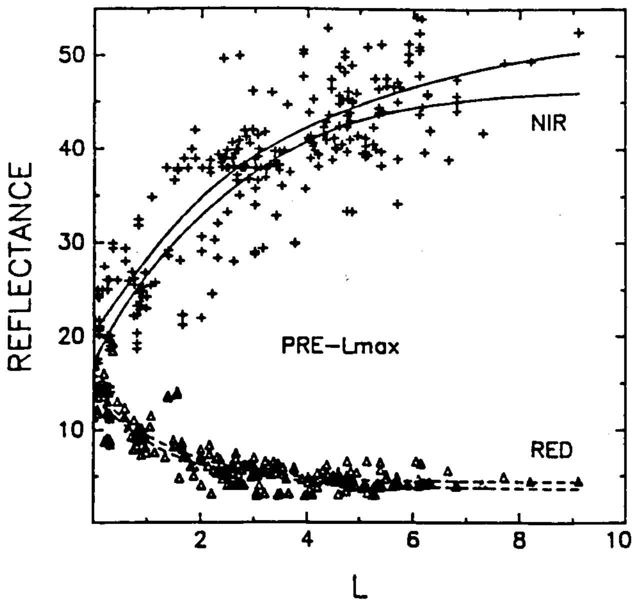
$$L(\text{post-}L_{max}) = -0.069 + 0.205(\text{PVI}),\quad r^2 = 0.74. \tag{11}$$

In Figure 4, the confidence limits of L overlap almost the full range of the data for the pre-L_{max} and post-L_{max} equations for TSAVI, NDVI, and PVI. Consequently, for these three indices, equations with coefficients intermediate between those in Table 5 for pre-L_{max} and post-L_{max} portions of the season would describe the data well over the whole season. The pre-L_{max} and post-L_{max} equations for RVI increasingly diverge at L values greater than about 2.0.

In summary of the pooled location findings of this study, the power equation form represented the data well for all VI. The power and exponential equation forms were equally useful for TSAVI and NDVI. The exponential form was less useful for PVI and RVI than the power form because it overestimated L at values below about 2. The relations for PVI and RVI were nearly linear. For TSAVI, NDVI, and PVI, equation coefficients intermediate between those for pre-L_{max} and post-L_{max} periods would describe the data well over the whole season.

RED and NIR reflectance. The upper and lower 95% confidence limits for the relation between the RED and NIR reflectance factors (R), in percent (%), and L pooled for all locations is shown by pre-L_{max} and post-L_{max} seasonal portions in Figure 5. A three-parameter exponential equation,

$$R = A_0 + A_1\exp(A_2 * L), \tag{12}$$



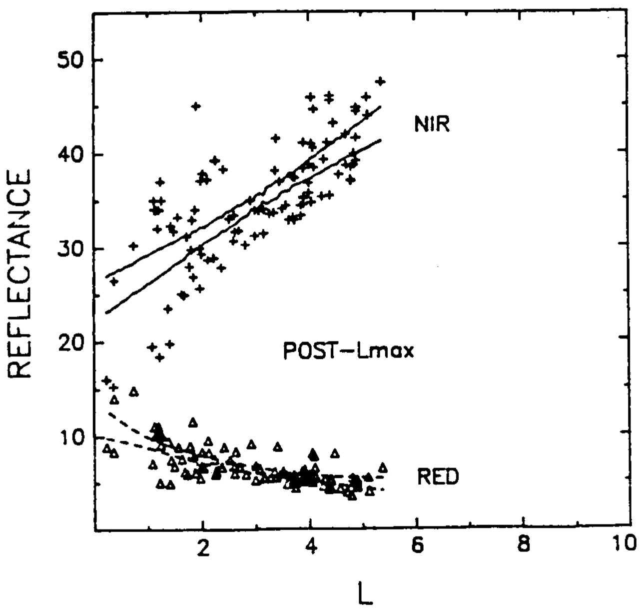


Figure 5. Scatter plots and 95% confidence intervals for the relation between RED and NIR reflectance (in percent) observations for all locations by pre-L_{max} and post-L_{max} seasonal portions expressed by Eq. (11), $R = A_0 + A_1 \exp(A_2 * L)$.

Table 6. A) Three-Parameter Exponential Relation [Eq. (12)] between RED and NIR Reflectance Observations across Locations by Pre-L_{max} and Post-L_{max} Seasonal Portions, and B) Linearized Values of Asymptotic Infinite Canopy (R_v) and Bare Soil (R_g) Reflectance in RED and NIR by Pre-L_{max} and Post-L_{max} portions of the Season Using Eq. (13)

A. Three-parameter exponential equations		
Pre-L_{max}	R^2	*RMSE*
RED = 3.97 + 10.165[exp(− 0.687) (L)]	0.80	1.56
NIR = 49.65 − 30.95[exp(− 0.337) (L)]	0.78	4.71
Post-L_{max}		
RED = 3.80 + 8.250[exp(− 0.407) (L)]	0.54	4.49
NIR = − 471.5 + 496.79[exp(0.0069) (L)]	0.52	1.44

B. Values of R_v, R_g, and k in Eq. (8)		
	Pre-L_{max}	*Post-L_{max}*
RED	$R_v = 4.0$	3.8
	$R_g = 14.2$	12.1
	$k = 0.69$	− 0.41
NIR	$R_v = 49.7$	− 471.5[a]
	$R_g = 18.7$	24.3
	$k = -0.337$	0.007

[a] Because this equation is essentially linear, it has no asymptotically limiting value. The unrealistic value of R_v is offset by the unrealistic value of the absorption-scattering coefficient k.

was fit to these data, and the resulting equations are given in Table 6, part A.

The coefficients of Eq. (12) can be linearized to the simplified plant canopy reflectance model given by Park and Deering (1982),

$$R = R_v - (R_v - R_g)\exp(-kL), \quad (13)$$

where R_v is the asymptotically limiting reflectance of the vegetation canopy, R_g is the reflectance of the bare soil, and k is the canopy absorption-scattering coefficient by letting $R_v = A_0$, $R_g = A_1 + A_0$, and $k = A_2$. An equation of the same form and interpretation of terms as just described for Eq. (13) has been independently derived in terms of VI and inverted to estimate L and the relative equivalent noise in those estimates for the indices TSAVI, NDVI, and RVI (Baret and Guyot, 1991).

The asymptotically limiting values of canopy reflectance in the RED (4.0%) and NIR (49.7%) and of soil reflectance in the RED (14.2%) and NIR (18.7%) are very reasonable for the pre-L_{max} portion of the season (Table 6B). However, the NIR response during the post-L_{max} portion of the season is so linear that an unrealistic value of infinite reflectance is estimated (there is no asymptotically limiting value for a linear function) that is offset by an unrealistically small absorption-scattering coefficient. In the RED, the values of R_v and R_g at 3.8% and 12.2% are not very different from their values during the pre-L_{max} portion of the season. However, during the post-L_{max} portion of the season $L = 0$ is reached by senescence of the plant canopy, so that all post-L_{max} values are for the composite senescent plant canopy–soil scene, not the bare soil alone. Shadows within the standing senescent plant material could make those values lower than for bare soil.

DISCUSSION

Figure 4 and the statistics of Table 5 indicate that the sorghum canopies, as characterized by the green leaf area index, strongly dominated the reflectance factor observations. Consequently, it was feasible to develop the generalized equations (Table 5) to recommend for predicting L of sorghum from spectral observations expressed as vegetation indices.

The results for grain sorghum herein are in good general agreement with the results for corn and wheat (Wiegand et al. 1990; 1992). Because of the similarity in growth habits and visual appearance of corn and sorghum (Wiegand et al., 1974) and in leaf display effects on absorbed, transmitted, and reflected solar radiation (Richardson and Wiegand, 1989), one would expect similar VI versus L equations for corn and sorghum. The across-location two-parameter exponential equations for corn obtained for NDVI and PVI during the pre-L_{max} part of the season by Wiegand et al. (1990) are very similar to relations presented for grain sorghum in Table 5. However, sorghum and corn may differ spectrally during the post-L_{max} period because of the development of heads and tassels in their respective canopies (Rosenthal et al., 1985).

A single equation might also hold over several different crops. For example, Redelfs et al. (1987) linearly related L of seven crops, sweet and field corn, grain sorghum, pearl millet [*Pennisetum americanum* (L.) Leeke], pinto bean (*Phaseolus vulgaris* L.), soybean, and sunflower (*Helianthus annuus* L.) to the four-band greenness vegetation index (GVI). They found they could use one equation for all the grassy (monocotyledonous) crops and a different equation for the broadleaf (dicotyledonous) crops.

Further evidence that the power equation developed here for sorghum (Table 5) is generally applicable comes from Maas (1988a), who used Landsat multispectral scanner digital counts for sorghum fields in the vicinity of Temple, Texas, converted to reflectances, for the NIR (0.8–1.1 μm) and RED (0.6–0.7 μm) bands and the equation,

$$L = 0.140 + 0.0392(\mathrm{PVI}{**}1.658), \qquad (14)$$

to estimate L during the 1973, 1975, 1976, and 1977 growing seasons for sorghum grown in the vicinity of Weslaco, Texas. The value of the coefficient A, 0.0392, in Eq. (14) is intermediate in value between those for the pre- and post-L_{max} portions of the season in Table 5 while the power, 1.658, is larger than the values 1.273 and 1.033 given in Table 5. However, it is risky to compare top of the atmosphere with ground measurements because of scattering by the atmosphere. Nonetheless, it is noteworthy that the equation form that best represented the Landsat data also best represented the ground measurements.

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